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Angular observation of joints of geckos moving on horizontal and vertical surfaces

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Because of their outstanding climbing and motor coordination ability, geckos have provided the basis for a peculiar bionic model leading to the development of a gecko-robot. A three-dimensional locomotion observation system was constructed to measure angular orientations of joints while geckos trotted (337.1 mm/s) and walked (66.7 mm/s) on horizontal surfaces, and trotted (241.5mm/s) and walked (30.6mm/s) on vertical surfaces. Moving over horizontal surfaces, the joints rotated more quickly the greater the speed, and the swinging scope of forelimbs stayed nearly at 59 degrees when swinging forward, but extended from 72 degrees to 79.2 degrees when swinging backward. The lifting angle of forelimbs was always positive to keep the center of mass close to the surface when moving up vertical surfaces, the scope of the forward swinging forelimbs forward extended from 33.7 degrees to 36.7 degrees with increasing speed, while the scope of backward swinging forelimbs remained almost the same at 87.5 degrees. Alternative gaits had little effect on the swing angle of hindlimbs of the geckos moving on both horizontal and vertical surfaces.

gecko, motor coordination, 3 dimensional observation, joint rotation

Locomotion involves the harmonious activity of the entire animal, depending especially on the coordinated action of muscles, bones, nervous system and sense organs[1]. Spatio-temporal gait characteristics and patterns of locomotive cycles are the collective results of the intrinsic properties and motion system of each animal[2–5]. Performance studies on animal locomotion refers to the interdisciplinary field of physiology and mechanics, which will not only help us to understand the regularity of animal locomotion, but also offer natural models and academic guidance on mechanical design, gait planning and control systems of bionic robots.

Over the long evolutionary periods of species, morphological characteristics of body and limbs have been optimized to improve the species' motion performance, particularly in adapting to special environmental circumstances. Morphological adaptations that permit scansorial habits are obvious, for example, adhesive pads, sculptured skin and flattened body shape of geckos, the claws of cats, and the suction cups of tree frogs.

The habitats of terrestrial tetrapods are usually rugged, consisting of ravines, inclines and cliffs. Animals must generate sufficient propulsive forces to move over steep or vertical substrata, not only to overcome inertia and environmental resistances from substrata and air, but also to counter gravity[6,7]. On inclines, forelimbs must pull on the substratum to avoid tumbling backwards while hindlimbs push to provide propulsion[6], and the center of mass close to the substratum is presumably

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beneficial for similar reasons. Scansorial animals often require different locomotive apparatus as evident when compared with ground-dwelling animals[8-11]. Research results show that level runners should have longer limbs, move more sagittally to increase stride length, and should elevate the body from the ground to reduce friction[7,12–14]. On the other hand, climbers should benefit from shorter limbs and a more sprawling gait to keep the center of mass as close to the substrate as possible[6,11,15,16].

In modern unstructured environments, robots are quite inferior to animals in regard to stability, agility, robustness, environmental adaptability, and energy efficiency[17]. Geckos have been the focus of scientific research because of their efficient and versatile adhesive abilities. They can attach and detach from various surfaces at will, mainly by exploiting van der Waals forces between the hierarchical structured setae on toes and contact surface[18–21]. Many studies on gecko's climbing abilities have been made with regard to the surface structure of the foot[22,23], the mechanisms of adhesion[19,22], adhesive strength[23–25], locomotive regulation[26,27] and the effect of external environments[28,29]. Moreover, morphology[7,9,14] and motion properties on vertical surfaces[4,11,30–32] have also been documented, but the disquisitions on angular variations of joints as geckos walk and trot over horizontal and vertical surfaces have not been reported. Experimental data will make a huge difference in research on the characteristics of motion and gaits from a space trajectory point of view, which can be avoided from the view of joints rotation. At present, the drive mechanism of a gecko robot depends mainly on micro-motors, and the planning and designing of motion are implemented based on angular orientation. Therefore, in the motion planning of gecko robots a more direct approach will be studying the orientation and angular changes of joints.

1 Materials and methods

Gekko gecko belongs to reptilia, squamata, lacertilian, gekkonidae. All animals were purchased from Guangxi, China, and fed adult mealworms in a special room regulated to simulate the ambient natural environment, temperature, humidity and normal rhythms of day and night in their habit.

The three-dimensional locomotion observation system consists of a tunnel and a high speed camera (Mikrotron, MC1311 Germany) (Figure 1). The tunnel is made up of a long soft wood box with two mirrors on each side mounted along its length and opened toward the camera at a 135° angle to the track. A transparent polymethyl methacrylate covers the top of the box. The high speed camera is supported with a tripod and connected with a computer to set the frame frequency, pixels, start and stop. During the experiments the locomotion process was digitally documented by the camera as pictures. The projection in each mirror gives the lateral position of joints and, together with the central image, full spatial poses were obtained. The tunnel is wide enough to enable the geckos to move freely. For horizontal locomotion, the tunnel was placed horizontally and the geckos were induced to move along from one end to the other, while for the vertical experiments the tunnel was mounted vertically and geckoes induced to move up from bottom to top.

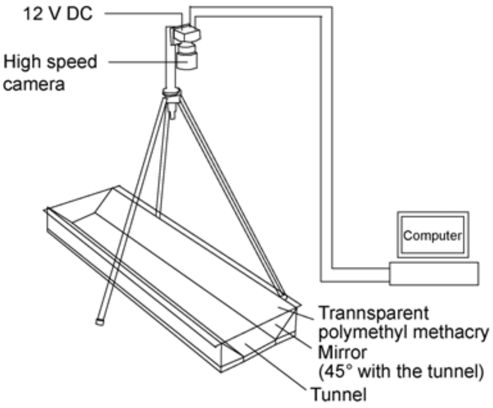

Figure 1 Three-dimensional locomotion observation system.

To describe the motion clearly and be in accord with our previous work, we define the references coordinates following the stereotaxic method[33]. We take the underside of tunnel in the three-dimensional locomotion observation system as the horizontal plane (body plane). The sagittal plane is the plane perpendicular to the body plane and passes through the bregma and nasal points. The coronal plane is the plane through the bregma point and perpendicular to the body plane and sagittal plane. The femorotibial angle (α) is the angle between femur and tibia, and is always positive. The swing angle (β) was calculated as the projection of the angle between femur and a plane through the coxa parallel with the coronal plane in the body plane. Swing angles in front of the parallel plane are considered positive, while behind this plane, negative. The lifting angle (γ) is defined as the projection of the angle between femur and a plane through the coxa parallel with the body plane in the coronal plane (Figure 2). Lifting angles are considered positive before the parallel plane, and negative behind this plane. The units of all angles are in degree (°).

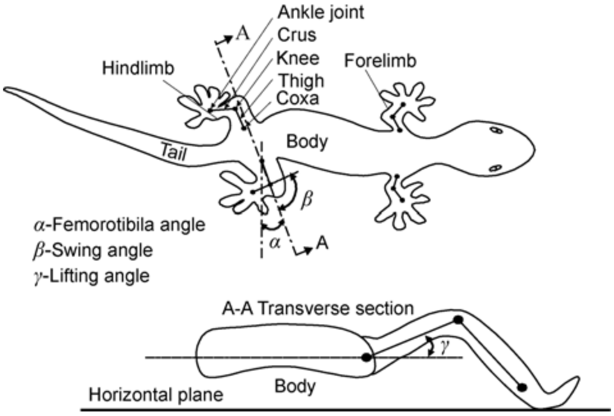

Figure 2 Angles defined.

Experiments were grouped by gait speed and surface orientation, viz., the quicker trot gait (trot) and slower tripod gait (walk) on both horizontal and vertical surfaces. The physical characteristics of the four selected geckos were similar except for weight. At least 20 gaits were recorded in each experiment. Linear regression of step length against time was done to assess the steady speed, and four groups of complete sequences were selected for further analysis for which the R^2 values of regression were greater than 0.95. All geckos selected were marked with white non-toxic painted dots on the coxa, knee and ankle joints before experiments. The camera axis was perpendicularly oriented to the locomotion surface (track) and adjusted until there was a clear image in the computer (Figure 3). The motion process was digitally recorded with a fixed frame frequency.

About 90－100 pictures were taken in one complete gait cycle. The coordinates (in the form of pixels) of all 24 dots in each picture were extracted by Sigma Scan Pro (SPSS Inc., Chicago, IL, USA) from which continuous joint angles could be derived. The coxa dot fixed on the body was taken as the reference point to calculate the speed of motion. Errors accrued in the process of calculating the coordinates from pictures as evident in the fluctuation of angular data. The Savitzky-Golay method was used in Origin Pro 8 (Origin Lab Corp., Northampton, MA, USA) to smooth the angular data. Variance analysis was done after filtering and the difference was considered to be insignificant compared with the original data if significance levels of 0.05 were reached.

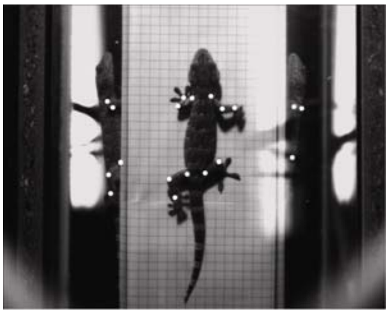

Figure 3 Image record.

2 Results

From our experimental data, it is found that there are no speed limitations in gait alternation between trotting and walking. Feet that are diagonally opposed might lift off and touch down at the same time even at slower velocities. Generally, when speeding up, geckos would transit from walking to trotting. The following four groups of data were selected for analysis and comparison: walking (66.7 mm/s) and trotting (337.1 mm/s) over a horizontal surface, and walking (30.6 mm/s) and trotting (241.5 mm/s) up a vertical surface. Extrema and ranges of fore and hindlimb angles are shown in Table 1.

2.1 Curves of limb angles

Spacio-temporal limb angles curves are the more intuitive ways to depict joint motion. The period of motion is normalized so as to be conveniently compared with that of different experiments. Joint angular curves of fore and hind limb over a gait cycle are shown in Figure 4.

One stance phase and one swing phase are included in one gait cycle, and there is one peak and one wave trough in the swing angle (*β*, solid line) and the lifting angle (*γ*, dashed line) curves in each cycle. The femorotibial angle (*α*, dash dot line) curve has one extension and one flexion in each phase, so there are two peaks and wave troughs in the curves. The lifting angle is maximal when swing angle is minimal in the angle curves of the forelimbs (Figure 4(a), (c), (e), (g)), but they are completely reversed in angle curves of hindlimbs (Figure 4(b), (d), (f), (h)). The swing angle has one local minimum in both the stance phase and swing phase, and the maximum appears in the transition between the two motion phases. The rules and trends of the curves are similar between different gaits in the same inclination, but the distinction is obvious when com-

Table 1 Extrema and ranges of fore and hindlimb angles (°)

Projects		Forelimb				Hindlimb			
		Horizontal		Vertical		Horizontal		Vertical	
		Trot	Walk	Trot	Walk	Trot	Walk	Trot	Walk
Swing angle	Max.	59.2	59.0	36.7	33.7	77.2	85.1	82.6	79.0
	Min.	–79.2	–72.0	–87.7	–87.3	–44.3	–31.1	–64.9	–53.3
	Ra.	138.4	131.0	124.4	121.0	121.5	116.2	147.5	132.3
Lifting angle	Max.	59.6	50.8	86.3	84.5	48.7	21.3	46.9	35.6
	Min.	–17.4	–11.4	15.5	5.4	–10.7	–18.0	–19.7	–16.7
	Ra.	77.0	62.2	70.8	79.1	59.4	39.3	66.6	52.3
Femorotibial angle	Max.	138.3	127.2	109.1	131.8	135.2	126.7	151.3	146.9
	Min.	39.3	47.7	55.2	56.3	54.4	78.7	51.1	47.5
	Ra.	99.0	79.5	53.9	75.5	80.8	48.0	100.2	99.4

pared in different inclinations, even for the same gait.

The gradient of the swing angle is greater in the swing phase than that in the stance phase, and is more obvious for forelimb compared with hindlimb. The tendencies of swing and femorotibial angles in forelimb are similar to those for hindlimb (Figure 4(a), (b), (c), (d)) when moving on horizontal surfaces. The gradient of the forelimb lifting angle is just like the swing angle (Figure 4(c), (g)). The lifting angle curve of the hindlimb is nearly symmetrical in the two motion phases when trotting on vertical surfaces. The differences in the three hindlimb angle curves are large on difference surfaces, but are similar over the same surface. The gradient of the hindlimb lifting angle is close to zero in 80% of the motion cycle (Figure 4(f), (h)).

The maximal swing angles of forelimb are nearly the same (about 59°), and there is a slight difference (about 7°) between the minimums with different gaits when moving on the horizontal surface, while on the vertical the minimums are nearly the same (about 87°), and about 3 degrees difference between the maximums. The differences among swing angle ranges of forelimb on the same inclination are 10 degrees. When moving on the vertical surfaces, lifting angle curves of forelimb are higher than those

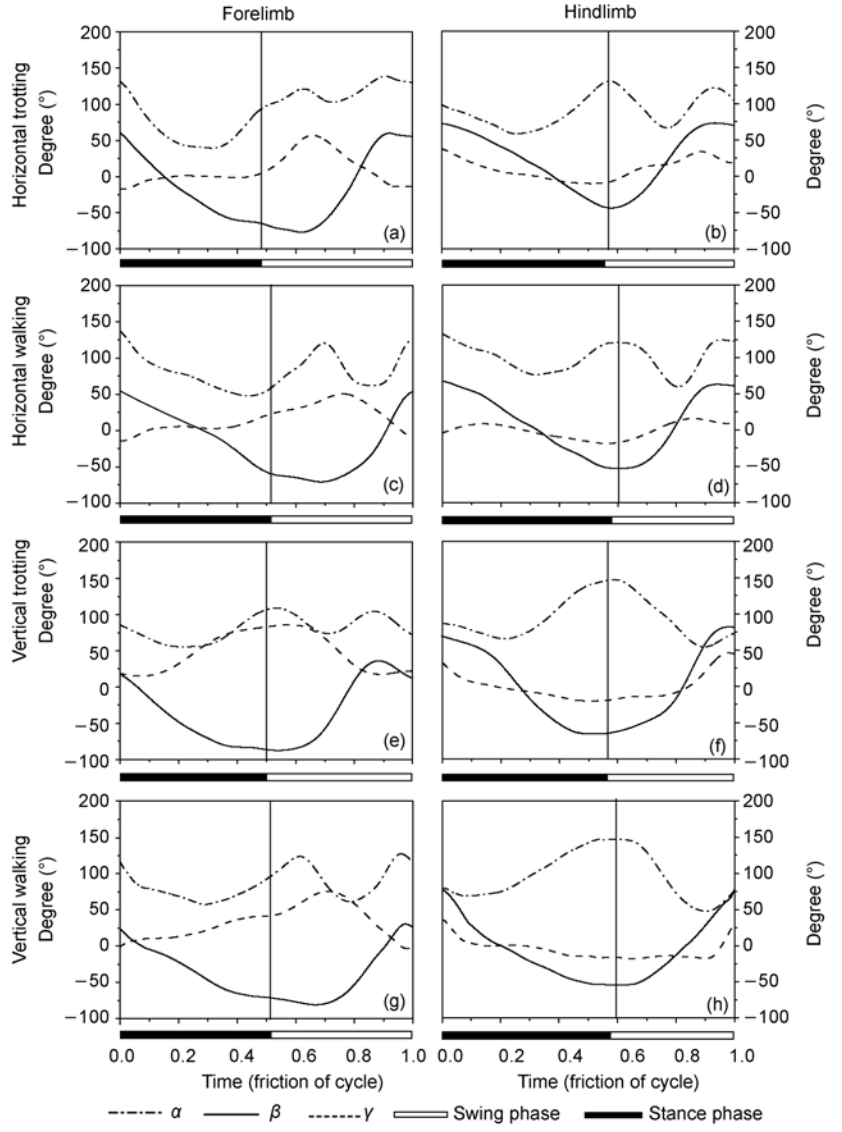

Figure 4 Curves of swing angle (*β*), lifting angle (*γ*) and femorotibial angle (*α*) in one cycle for gecko trotting ((a) for forelimb and (b)) for hindlimb, walking (c) for forelimb and (d) for hindlimb on horizontal surface, and corresponding curves of trotting ((e) for forelimb and (f) for hindlimb) and walking ((g) for forelimb and (h) for hindlimb) on vertical surface. The perpendicular is the division of swing phase (black filled line) and stance phase (white filled line).

when moving over level surfaces with the same gait, and the values are all positive (Table 1, Figure 4), while the gap of the forelimb lifting angle ranges is less than 10° except when moving over level surfaces (62.2°). Femorotibial angles are the largest (99°) when trotting horizontally, and are the least when trotting vertically (53.9°). For the hindlimbs, the joint rotation ranges are larger when moving vertically than those when moving horizontally after comparing each group. Over the same inclined surfaces, the ranges of each angle increase with increasing speed, and are larger when moving vertically than those when moving horizontally with the same gait.

2.2 Angle-angle plots

Angular phase diagrams are used to show the relationship and tendencies of the two groups of angles with the same time variable[34]. The shape of the phase diagram shows the changing trend of angles in different phases, and the position in the coordinate system shows the angle scope. It is very convenient to compare the same group of data in different states by their phase diagrams. The phase diagrams of swing-lifting angles and swing-femorotibial angles are shown in Figure 5. Arrows in each figure indicate the direction of joint rotation, and swing phase is at the beginning. The time interval between two sequential plots in a diagram is the same, so the speed in each phase can be evaluated by the density of dots—the slower the movement the denser the points. Closed loops indicate periodicity, and the enclosed area shows the changing extent of joint angles between swing phase and stance phase.

When trotting over horizontal surfaces, swing-lifting angle plots of fore and hind limbs (Figure 5(a), (e)) and the swing-femorotibial angle plot of forelimb (Figure 5(i)) are clearly different from other plots. The density of dots is greater when swinging forward than that when swinging backward in relation to the arrow's direction.

There is a great difference in the shape of phase diagrams due to the different velocities when moving over

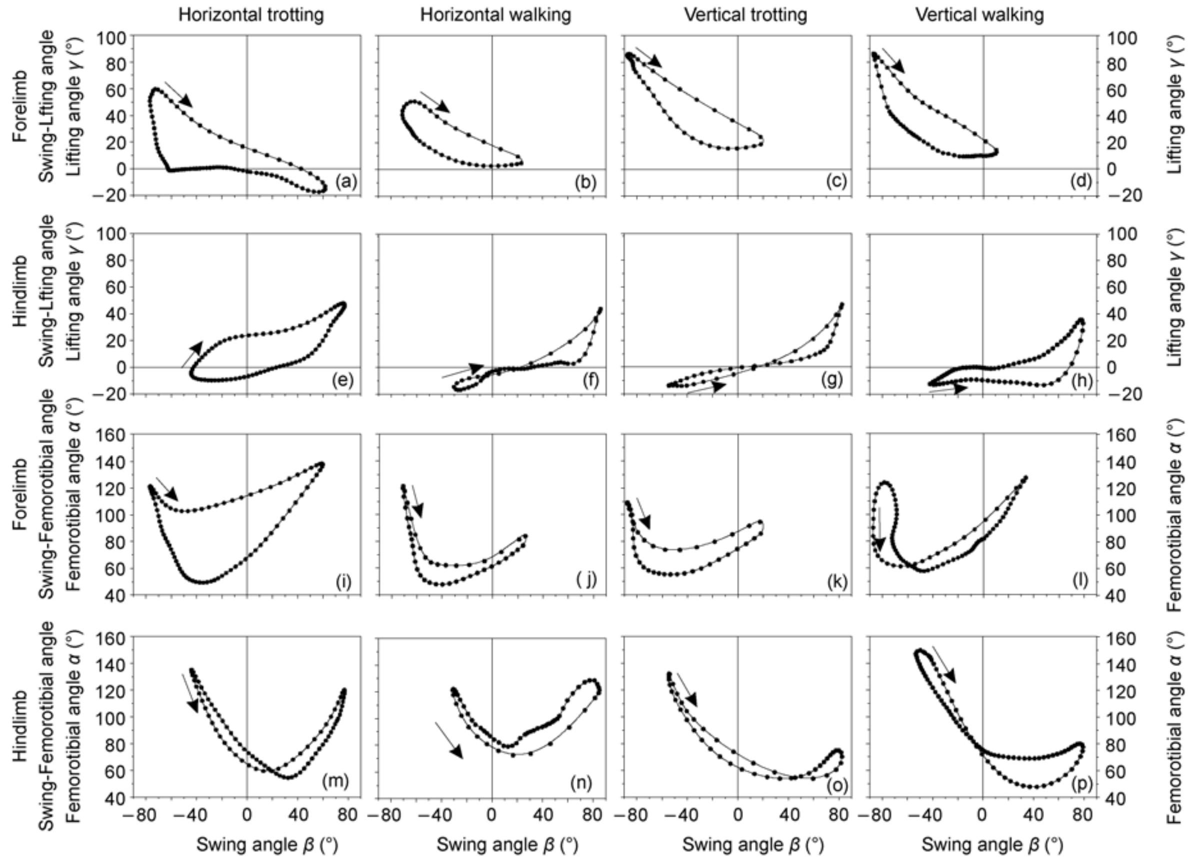

Figure 5 Swing-lifting angle plots for forelimb trotting (a) walking; (b) on horizontal surface, trotting; (c) and walking; (c) on vertical surface; (e), (f), (g), (h) are the corresponding plots for hindlimb; (i), (j), (k), (l) are swing-femorotibial angle plots for forelimb; (m), (n), (o), (p) for hindlimb respectively. Dots represent time slices and speed trend can be estimated by the density of dots. The arrow in each phase diagram represents the change direction of curve. Time interval of trotting and walking on horizontal surface and trotting and walking on vertical surface are 4 ms, 25 ms, 10 ms and 20 ms respectively.

horizontal surfaces, but the swing-femorotibial angle plot of the hindlimbs are similar (Figure 5(m), (n)). The enclosed areas of the swing-femorotibial angle plot in fore and hind limbs increase with the increasing speed (Figure 5(a), (b), (e), (f)). The change of femorotibial angle in forelimb is slight in the swing phase, but large bending exists in the stance phase (Figure 5(i)). The trends of the swing-lifting angle plot for forelimb (Figure 5(a)—(d)) and hindlimb (Figure 5(e)—(h)) are reversed in correspondence with the forelimb's angle curves in Figure 4. Compared with moving on horizontal surfaces, there is a lot in common between each group of phase diagrams in different gaits up vertical surfaces. And the forelimb swing- lifting angle plots (Figure 5(c), (d)) are the most obvious among these groups. Shape almost remained the same, except the position in the coordinate system when moving up vertical surfaces, which shows that the angular velocity of joints increases with speed, but the mode of joint rotation nearly keeps invariant. The swing-lifting angle plots are higher when moving up vertical surfaces than those when moving over horizontal surfaces (Figure 5(a)—(d)), and the positions as seen in Figure 5(c), (d) are all above the zero line, which means that the thigh has swung above the plane that crosses the coxa and parallels the body plane, placing the center of the body closer to the motion surface.

3 Discussions

Morphology differences[7] between forelimb and hindlimb endow the gecko with the possession of a special adaptation. The shorter forelimb is shaped to climb. The thigh moves forward at the end of the swing phase and moves mostly hindward at the end of the stance phase. The relative height between coxa and foot in the forelimb is maximal at the end of swing phase. Regarding the coordination and compliance of movement, the limbs do not move forward at the moment of lift off, but continue to move backwards to avoid the abrupt change in acceleration.

3.1 Influence of locomotion speed on joint rotation

The diagonal gait is used when geckos move at high speed, that is, the motion cycles of fore and hind legs diagonally opposed are almost the same. The triangle gait is engaged at low speeds, namely, each swing in turn is based on the order of front right-hind left-front left-hind right-front right. Different strategies during speed adjustments are adopted when moving over horizontal and vertical surfaces at different gaits.

The experiment performed by Zaaf et al. showed that stride frequency increased when speeding up, but step length, stride and duty factor remained unchanged when geckos moved over horizontal surfaces, and hindlimb moved more parasagittally. Both step length and stride frequency increased with increasing speed up vertical surfaces, but the relative increase of step length was small compared with that of stride frequency[31]. According to the results of Zaaf et al., joint angles exhibited the following rules: angular velocity should rise with increasing locomotion speed over horizontal surfaces, but the scope of swing angle remain unchanged, and the curve of the lifting angle in the stance phase should be lower to decrease the angle between thigh and sagittal plane; angular velocity should rise with increasing locomotion speed up vertical surfaces, and the scope of the swing angle should increase. Rotation speed of the joint should increase with increasing locomotion speed over the same surface, which could be derived from the dot density in the phase diagrams in Figure 5. The curve of the lifting angle corresponding to horizontal trotting was lower than that up vertical surfaces. Increased amplitude of hindlimb swing angle with increasing speed up vertical surfaces is obvious (Table 1). This experimental result was proved by our angular measurements. Moreover, in our experiments, the swing angle increase of the hindlimb was accomplished mainly during the backward swing, but did not change much during the forward swing.

When geckos trot horizontally, the task of the forelimb in the swing phase is completed by the forward extension of the crus carried by the forward rotation of the coxa, while the femorotibial angle almost remains unchanged at the end of the stance phase. The performance looks quite smart and quick. The lifting range of the fore thigh in trotting is larger than that in walking to avoid collisions between the limb and blocks (such as stones and so on) in swing phase and body drag over the locomotion surface.

3.2 The differences of joint rotation between moving on horizontal and vertical surfaces

Over horizontal surfaces, the body is supported by four legs on the substratum by overcoming gravity, friction and forward propulsion. Up vertical surfaces, there is the risk of tumbling backwards because of the moment of inertia when the body's center of mass leaves the wall. This moment of inertia is proportional to the gecko's mass and the perpendicular distance between center of mass and the wall. The influence of the moment of inertia is compensated by the pulling force of the shorter forelimb against the wall, and the torque due to the fact that the limbs in the swing phase overcome the gravity and also offer enough propulsion to move the body upward[32].

The moment of inertia is decreased by reducing the distance between the center of mass and the vertical surface. This is done with the thighs in the stance phase being displaced from above to below the plane that crosses the coxa and paralleling the body plane. The lifting angles of the hindlimb are at the lowest position during most of the motion cycle, and the curves are very flat. Locomotion velocity has little influence on each limb's motion style (the shapes of the phase diagrams remain nearly the same). Over horizontal surfaces, limbs just need to overcome gravity and support propulsion, so the motions of limbs are more sprightly and agile.

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